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High Resolution Focusing for Near field GPR Imaging

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Abstract—In this paper, we present an analysis of High Resolution techniques combined with migration methods in Ground Penetration Radar (GPR) systems. We focus on improving the detection of close targets which is limited by the signal bandwidth and synthetic aperture length for conventional imaging techniques. Increase in azimuth resolution is showcased by the ability to distinguish targets separated by less than the theoretical azimuth resolution in near-field wide-band configurations.

I. INTRODUCTION

In Ground Penetration Radar (GPR) imaging, target shows up as hyperbola therefore migration techniques are required to localize their true position [1]. However, their performance in terms of spatial resolution is limited by spectral bandwidth and the dimensions of the GPR synthetic aperture. To overcome this, we propose to use High Resolution (HR) methods, originally used for antenna array processing based on a data model with assumptions of a planar wave and narrow bandwidth configurations [2]. When the GPR data are acquired in a wide-band near-field configuration the spherical curvature of the wavefront generates nonlinear migrations of the spatial subdivision cells. Their imperfect compensation using the planar wave assumption then generates residual range shifts whose magnitude can be comparable to the range resolution. Since the HR methods studied use the covariance matrix of a restricted range of the GPR data, the selected vector will provide only a portion of the phase history of the target response. Hence, the ability of HR methods to distinguish closely spaced targets is reduced. Here, we focus on improving the azimuth resolution by first compensating for near-field and wide-band effects using migration algorithms.

II. CASE STUDY

In this study we use a FDTD tool [3] to simulate 20 antennas arranged along the x -axis spaced by $\lambda_{eff}/4$ which is the effective electrical length in a dielectric medium with permittivity $\epsilon_r = 5$. The medium is assumed to be homogeneous, non-magnetic and lossless. A Ricker waveform with a center frequency of 0.5 GHz and a bandwidth of 2 GHz is used. Targets are perfect electric conductor spheres with 2 mm radius. The theoretical resolution in our configuration is equal to 18 cm along x and 3.35 cm along z .

In Fig. 1 we show the different scenarios investigated: 1 target at $z=0.8$ m (a) ; 2 targets separated by dx at $z=0.8$ m in the middle of the array, i.e. $x=0.3$ m (b); 2 targets separated by dx at $z=0.8$ m on a side azimuth position with respect to the centre of the array i.e. $x=0.5$ m (c). In Fig. 2 we show that BP

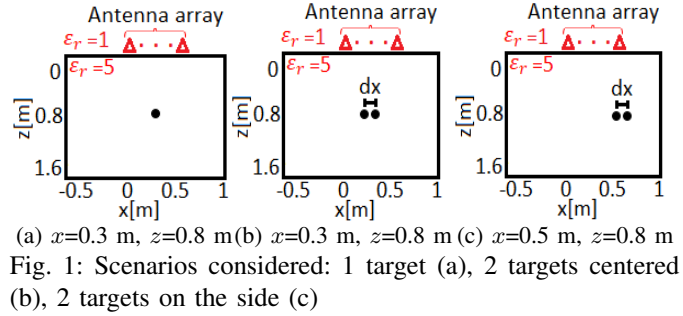


Fig. 1: Scenarios considered: 1 target (a), 2 targets centered (b), 2 targets on the side (c)

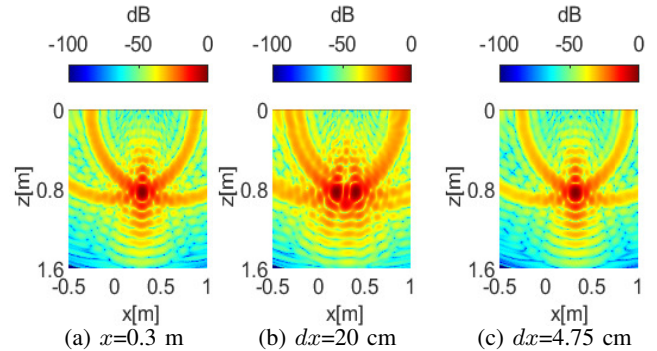


Fig. 2: BP results: Scenario 1 (a), Scenario 2 with $dx=20$ cm (b), Scenario 2 with $dx=4.75$ cm (c).

is efficient for 1 target (a) or far enough 2 targets (b). When the offset was changed to 4.75 cm which is about a quarter of the azimuth resolution, BP interpreted the two targets as a single target as in Fig. 2(c). To improve resolution, HR techniques are implemented by selecting a range cell from BP focused data where the near-field broadband effects have been compensated. However, in near-field wide-band configurations the target 2D ambiguity function spreads on multiple range cell especially

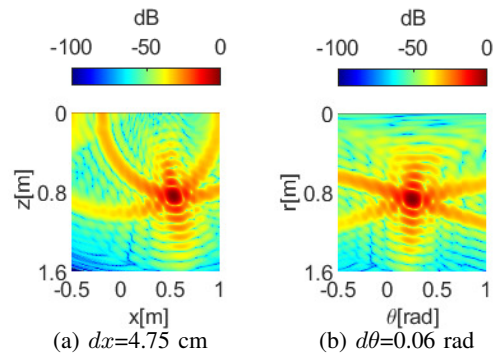


Fig. 3: BP results in Scenario 3 with $dx=4.75$ cm: cartesian (a) and polar projection (b).

for targets at squint angles (on side of array) as in Fig. 3(a). In this case, selection of one range cell is not valid anymore as only partial information is selected. Therefore, we propose to implement BP in polar grid that follows the 2D ambiguity function of targets. This implies non uniform sampling of range and angle that can be transformed to Cartesian coordinates that are dense near the array and sparse away from the array i.e i th pixel with $x = r_i \sin \theta_i$ and $z_i = r_i \cos \theta_i$. By doing so, the selection of one particular range cell gives full information about the target behavior as seen in Fig. 3(b).

III. ADAPTATION OF HIGH RESOLUTION TECHNIQUES

HR methods are applied in azimuth so spectral diversity is obtained from an aperture sampled in spatial domain. Based on the signal model defined in [2] [4] [5], the HR methods analyzed are covariance matrix based algorithms including: (i) Beamforming (BF); (ii) Capon's (CP); (iii) Multiple Signal Classification - MUSIC (MU); (iv) MUSIC-Root (MUroot); (v) Orthogonal Projector Method (OPM); (vi) OPM-Root; (vii) Estimation of Signal Parameters via Rotational Invariant Techniques (ESPRIT); (viii) Deterministic Maximum Likelihood (DML); and (ix) Weighted Signal Subspace Fitting (SSF). Each of the methods is based on the assumptions that the covariance matrix is poorly correlated or not correlated at all. Nevertheless, the received GPR data are generally correlated.

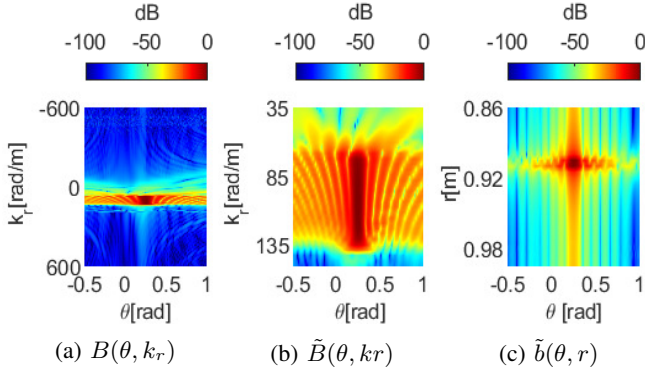


Fig. 4: Range smoothing in Scenario 3: FT of BP (a) BP selected spectrum (b), IFT of selected BP spectrum (c)

To ensure the non-singularity of the covariance matrix, spatial smoothing is applied [2]. It divides an array with N elements into smaller overlapping subarrays with N_{sub} elements. Then it average the data covariance matrices obtained from each subarray. This option reduce resolution from $1/N$ to $1/N_{sub}$. So, we propose to use range smoothing that keep full array elements N hence maximizing the azimuth resolution.

The algorithm developed in this work is based on the following steps: (i) the GPR data $H(x, f)$ are deconvoluted by the Wiener filter to compensate the Ricker waveform; (ii) $H(x, f)$ is focused by BP to obtain $b(\theta, r)$ then Fourier transform (FT) is applied to have $B(\theta, k_r)$ as in Fig. 4(a); (iii) Range smoothing is done by selecting useful spectrum, $\tilde{B}(\theta, k_r)$ shown in Fig. 4(b) followed by Inverse FT $\tilde{b}(\theta, r)$ as in Fig. 4(c); (iv) Range cell is selected from $\tilde{b}(\theta, r)$ then FT to get $\tilde{B}(k_\theta, r = r_0)$; (v) Finally, HR methods are applied to

the range smoothed spectrum for position estimation ($P(\theta_i)$).

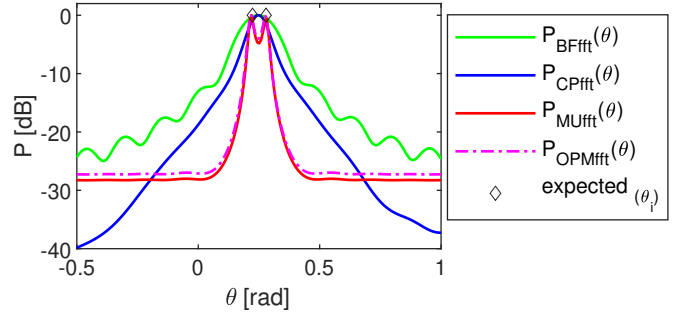


Fig. 5: Mono-dimensional HR results in Scenario 3

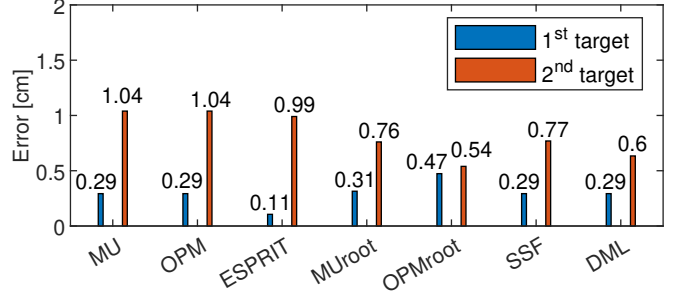


Fig. 6: HR Estimated position errors for Scenario 3

The results show that the non-parametric methods (BF and CP) did not distinguish the close targets as seen in Fig. 5 because their resolution is limited by the number of antennas. However, other methods were able to discriminate targets separated by less than the azimuth resolution with an error of less than around 1 cm as shown in Fig. 6. The parametric methods (MUSIC, OPM, Root-MUSIC, Root-OPM, and ESPRIT) have a better resolution because they depend on the quality of the estimate of covariance matrix. SSF and DML are multidimensional parametric methods that estimate position by optimizing predefined criteria. The latter are more robust and have a high overall accuracy despite a high computational cost.

IV. CONCLUSION

Since the HR techniques are based on narrow-band wave assumptions, broadband near-field compensation was performed by migration methods projected on polar grid. Range smoothing was used for decorrelation thus two targets separated by less than the azimuth resolution was correctly distinguished.

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